Evidence for single top quark production at DØ

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Tollestrup award

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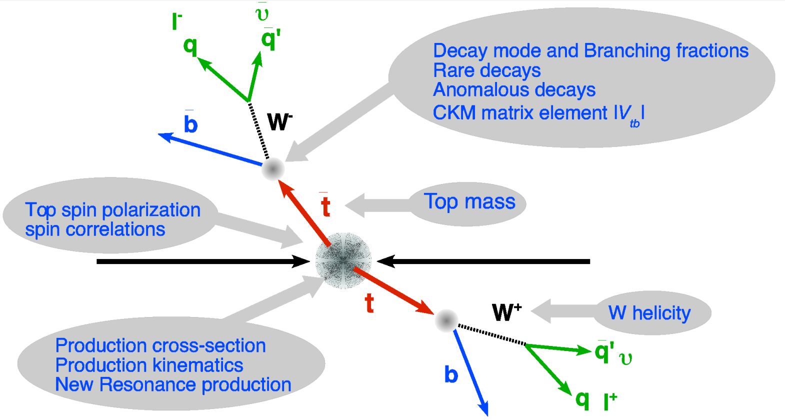
Top quark physics

- top quark discovered in 1995 by CDF and DØ at the Tevatron
- Heaviest of all fermions
- Couples strongly to Higgs boson
- So far only observed in pairs, only at the Tevatron



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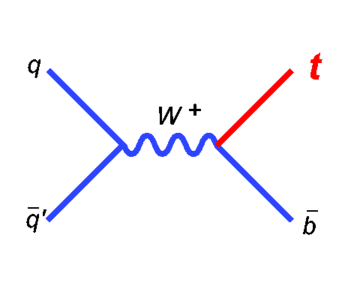
Single top quark production

- Never observed before: electroweak production

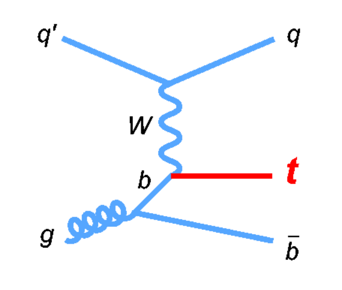
s-channel (tb)



- $\sigma_{NLO} = 0.88 \pm 0.11$ pb (*)
- previous limits (95% C.L.):

Run II DØ: < 5.0 pb (370 pb^{-1})
Run II CDF: < 3.1 pb (700 pb^{-1})

t-channel (tqb)



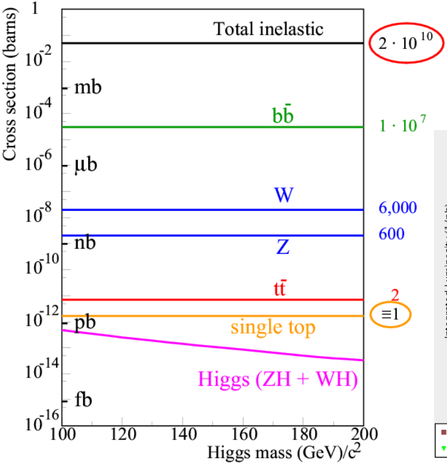
- $\sigma_{NLO} = 1.98 \pm 0.25$ pb(*)
- previous limits (95% C.L.):

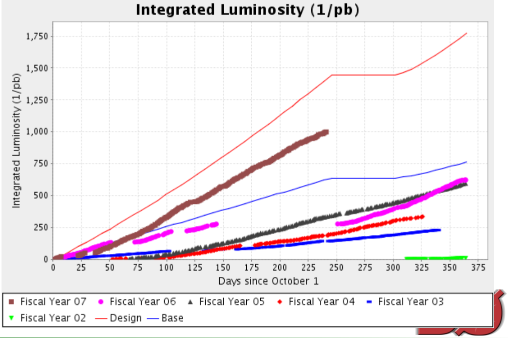
Run II DØ: < 4.4 pb (370 pb^{-1})
Run II CDF: < 3.2 pb (700 pb^{-1})

(*) $m_t = 175$ GeV, Phys.Rev. D70 (2004) 114012

It has been challenging for years...

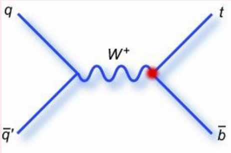
- Several publications since Run I by DØ and CDF
- 7 DØ and 6 CDF PhDs (Dec '06)
- $\sigma_{t\bar{t}}$ only $\sim 2 \times \sigma_{singletop}$, but has striking signature

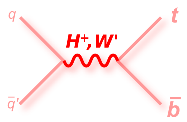


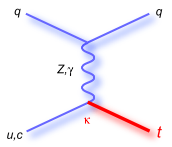


Why do we care? — $|V_{tb}|$, new physics

- Has never been observed before!
- It should happen in SM
- First measurement of $|V_{tb}|$







Direct access to $|V_{tb}|$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- In SM, from constraints on V_{td} and V_{ts}: $|V_{tb}| = 0.9991^{+0.000034}_{-0.000004}$
- New physics, e.g. 4^{th} generation: $0.07 < |V_{tb}| < 0.9993$

New physics

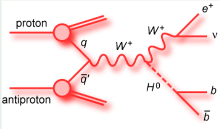
- s and t channel cross sections differently sensitive
- s-channel: charged resonances (heavy W' boson, charged Higgs boson, charged top pion, etc.)
- t-channel: new interactions (FCNC, 4^{th} generation, etc.)

Why do we care? — Spin, Higgs, analysis techniques

Top quark spin

- Large mass $\Rightarrow$ top quark decays before it can hadronize (no top jets)
- First chance to study a bare quark!
- Top polarization reflected in angular distributions of decay products
- SM predicts high degree of left-handed tops $\Rightarrow$ possible sign of new physics, or help pin down what new physics

Higgs searches



- Important background to *WH* associated Higgs production
- As soon as we discover it, somebody will try to get rid of it....

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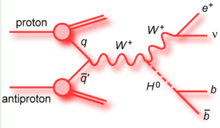

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Advanced analysis techniques

- Test of techniques to extract small signal out of large background
- If tools don't work for single top, forget about the Higgs and other small signals
- If tools don't work at Tevatron, not much hope for LHC

Multivariate analysis techniques

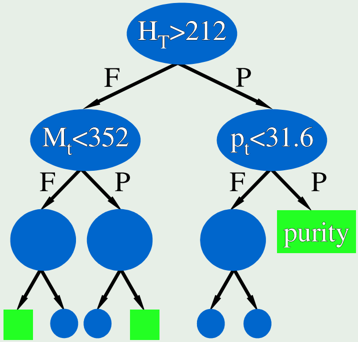
- Bayesian neural networks
- Matrix element
- Boosted decision trees

- All three analyses have similar sensitivity and give compatible measurements
- Details about decision trees only today

Decision trees

- Machine-learning technique, widely used in social sciences
- Idea: recover events that fail criteria in cut-based analysis

- Start with all events = first node
  - sort all events by each variable
  - for each variable, find splitting value with best separation between two children (mostly signal in one, mostly background in the other)
  - select variable and splitting value with best separation, produce two branches with corresponding events ((F)ailed and (P)assed cut)
- Repeat recursively on each node
- Splitting stops: terminal node = leaf



- DT output = leaf purity, close to 1 (0) for signal (bkg)

Ref: Breiman *et al*, "Classification and Regression Trees", Wadsworth (1984)

Splitting a node

Impurity $i(t)$

- maximum for equal mix of signal and background
- symmetric in p_{signal} and $p_{background}$
- minimal for node with either signal only or background only
- strictly concave $\Rightarrow$ reward purer nodes

- Decrease of impurity for split s of node t into children t_L and t_R (goodness of split):
  $\Delta i(s,t) = i(t) - p_L \cdot i(t_L) - p_R \cdot i(t_R)$
- Aim: find split s^* such that:

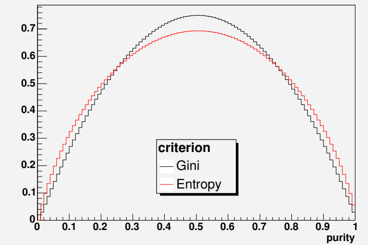
$$\Delta i(s^*,t) = \max_{s \in \{\text{splits}\}} \Delta i(s,t)$$

- Maximizing $\Delta i(s,t) \equiv$ minimizing overall tree impurity

Examples

$Gini = 1 - \sum_{i=s,b} p_i^2 = \frac{2sb}{(s+b)^2}$

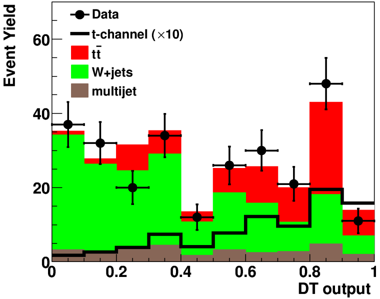
$entropy = -\sum_{i=s,b} p_i \log p_i$



Decision tree output

Measure and apply

- Take trained tree and run on independent pseudo-data sample, determine purities
- Apply to data
- Should see enhanced separation (signal right, background left)
- Could cut on output and measure, or use whole distribution to measure



Limitations

- Instability of tree structure
- Piecewise nature of output

Advantages

- DT has human readable structure (no black box)
- Training is fast
- Deals with discrete variables
- No need to transform inputs
- Resistant to irrelevant variables

Boosting a decision tree

Boosting

- Recent technique to improve performance of a weak classifier
- Recently used on decision trees by GLAST and MiniBooNE
- Basic principal on DT:
  - train a tree T_k
  - $T_{k+1} = \text{modify}(T_k)$

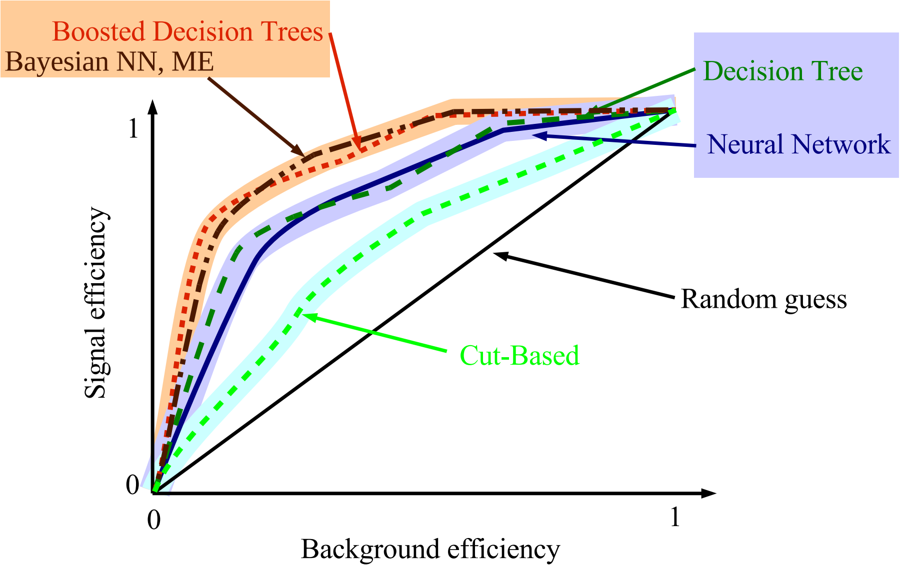
AdaBoost algorithm

- Adaptive boosting
- Check which events are misclassified by T_k
- Derive tree weight α_k
- Increase weight of misclassified events by e^{α_k}
- Train again to build T_{k+1}
- Boosted result of event i: $T(i) = \sum_{n=1}^{N_{\text{tree}}} \alpha_k T_k(i)$

- Averaging ⇒ dilutes piecewise nature of DT
- Usually improves performance

Ref: Freund and Schapire, "Experiments with a new boosting algorithm", in *Machine Learning: Proceedings of the Thirteenth International Conference*, pp 148-156 (1996)

Comparison



Boosted Decision Trees
Bayesian NN, ME
Decision Tree
Neural Network
Random guess
Cut-Based
1
0
0
1
Signal efficiency
Background efficiency

Analysis validation

Ensemble testing

- Test the whole machinery with many sets of pseudo-data
- Like running DØ experiment 1000s of times
- Generated ensembles with different signal contents (no signal, SM, other cross sections, higher luminosity)

Ensemble generation

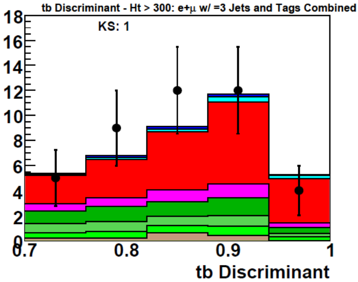
- Pool of weighted signal + background events
- Fluctuate relative and total yields in proportion to systematic errors, reproducing correlations
- Randomly sample from a Poisson distribution about the total yield to simulate statistical fluctuations
- Generate pseudo-data set, pass through full analysis chain (including systematic uncertainties)

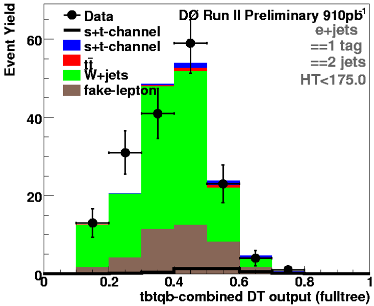
All analyses achieved linear response to varying input cross sections

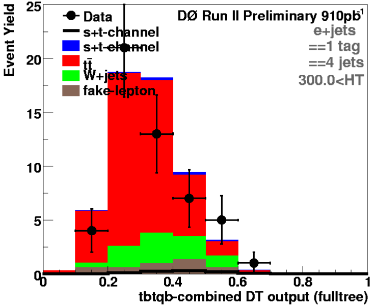
Cross-check samples

- Validate methods on data in no-signal region
- **"W+jets":** $=$2jets, H_T(lepton,$\not\!\!E_T$,alljets) < 175 GeV
- **"ttbar":** $=$4jets, H_T(lepton,$\not\!\!E_T$,alljets) > 300 GeV
- Good agreement

ME "hard W+jets": $=$3jets, $H_T > 300$ GeV

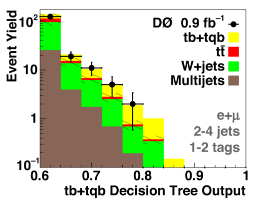


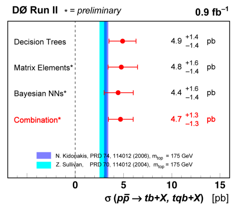




Results

First evidence for single top quark production (DØ decision trees)





$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 4.9 \pm 1.4 \text{ pb}$$

3.4σ significance

First direct measurement of $|V_{tb}|$ (DØ decision trees)

$$|V_{tb} f_1^L| = 1.3 \pm 0.2$$

assuming $f_1^L = 1$: $0.68 < |V_{tb}| \leq 1$ @ 95% CL

(Always assuming $V_{td}^2 + V_{ts}^2 \ll V_{tb}^2$ and pure $V{-}A$ and CP-conserving Wtb interaction)

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Single top prospects — Tevatron and LHC

Tevatron

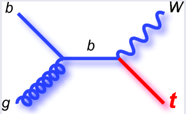
- By 2008 we should have observed single top production and measured its cross section to 15-20%
- $|V_{tb}|$ is then known to $\sim$10%

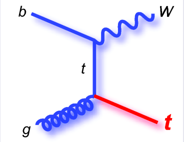
LHC

- Much larger production rates:

$$\sigma_s^{t/\bar{t}} = 6.6/4.1 \text{ pb } (\pm 10\%)$$
$$\sigma_t^{t/\bar{t}} = 156/91 \text{ pb } (\pm 5\%)$$
$$\sigma_{tW}^{t/\bar{t}} = 34/34 \text{ pb } (\pm 10\%)$$

- Try to observe all three channels (s-channel challenging)
- $|V_{tb}|$ measured to percent level
- Large samples $\Rightarrow$ study properties





Thank you!

A long and complex process

- Many parts in the analysis
- Detailed understanding and modeling of data
- Many people involved over many years

Thank you to

- Dugan O'Neil, Dag Gillberg and the Simon Fraser University group
- Gordon Watts and Toby Burnett at University of Washington
- the single top working group at DØ
- the top quark physics group
- the single top quark Editorial Board members
- the other DØ experiment groups and the Accelerator Division
- ... competitors across the ring that made us rise up to their challenge